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SAR Interferometry and Surface Change Detection

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Workers put final touches on new AGU headquarters.

Although slightly short of turn-key status, the building was nonetheless raring to go by move-in time. The entire palette of the building has been designed in Earth tones, from the peach and grey granite and mahogany woodwork of the entrance hall to the cool teals, blues and grays of most of the work space.

Individual workspaces are outfitted with modern desks and furniture, while special energy saving lights and sound absorbing ceiling tiles top off the nine-foot high ceilings throughout the five-story structure. Each of the floors also has smaller conference rooms.

The new building also has a new fiber optic network to facilitate a faster and more effective computer information system. In addition, AGU continues to upgrade its computer network by acquiring more modern technology and faster Internet connections. Spilhaus explains that the whole idea of the building was to make AGU more efficient, both in terms of working space and cost of operations. AGU secured financing for the project through a 30-year tax-exempt bond at a rate of approximately 5.9% through the District of Columbia.

The building will benefit the community it serves not only by bringing a contemporary image to AGU, but also by enhancing services provided to the members. Specifically, the new headquarters will work to make AGU meetings, communications, and publishing of geophysical literature more efficient. Overall, Spilhaus says the new headquarters are "much more usable than the previous space."

The new headquarters house 60,000 square feet of rentable space, some of which

will be leased. The American Astronomical Society, for example, will continue to rent space from AGU. The building will allow the AGU staff to double in size. Even if over the course of the next couple decades AGU's growth continues at current levels, new trends in the workplace will mean the building will actually be able to accommodate much more growth, Spilhaus predicts. For example, in the future, as the "information-oriented" society continues to emerge, more and more workers will work from the home, he says.

SAR Interferometry and Surface Change Detection: Workshop Held

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Recent events have brought synthetic aperture radar (SAR) interferometry into vogue—at least in some sectors of the geophysical science community. For one thing, the image of coseismic displacement associated with the Landers earthquake, recently published in *Nature* [Massonnet *et al.*, 1993], coupled with the recent disastrous Northridge earthquake of January 17, 1994, has created interest in the Earth science community about SAR interferometry. In particular, there is widespread appreciation that this technique can make a significant contribution to earthquake studies in California and other tectonically active regions.

Similarly, a recent demonstration that ice stream velocity could be measured directly from space without ground control points using SAR interferometry [Goldstein *et al.*, 1993] has caught the attention of the polar science community. However, many scientists are not familiar with SAR interferometry, and the strengths and limitations of the technique need to be explored.

To consider existing and new applications of SAR interferometry and to recommend ways of enhancing collection and distribution of data, thirty-seven scientists representing a broad range of Earth sciences met in Boulder, Colo., on February 3 and 4, 1994. The first morning included a tutorial on the technique. Then, attendees divided into six discipline-specific groups (volcanos; earthquakes and faulting; mountain building and erosion; ice sheets and glaciers; hydrology, ecosystem studies and environmental monitoring; and technology) to discuss applications and make recommendations. A great deal of discussion focused on what is actually being measured by an interferometric SAR, the time span over which a useful "change" signal can be detected in a specific environment, and what happens to the surface during "temporal decorrelation," or loss of coherence after some period of time.

The second morning began with a description of existing or planned radar missions (European Space Agency's ERS-1 and 2, Japan's JERS, NASA's shuttle-mounted SIR-C and possible SIR-C "free flyer," and Canada's Radarsat). NASA's DC-8 aircraft-mounted AIR-SAR was also described, along with the Global Topography Mission (TOPSAT). The Global Topography Mission, currently under study by NASA, is a dual-spacecraft system, each spacecraft equipped with an L-band (24-cm wavelength) SAR, a laser altimeter, and a Global Positioning System receiver for high-accuracy orbital tracking. The two spacecraft would orbit about 1 km apart to form the interferometer baseline, acquiring high-resolution, high-accuracy topographic data over the entire globe within 3 months. The duration of the main mission as currently configured is only 9 months, but it could be easily extended to 3 years to enhance change detection capability.

Background

Interferometric SAR exploits the coherent nature of radar, by using changes in the phase of the reflected signal in the before and after images to determine changes in the location of the ground surface to a precision of a fraction of a radar wavelength, or about a centimeter. The changes are averaged over a surface picture element or pixel, (typically tens of meters in diameter). In the case of coseismic changes (actually the sum of pre-seismic, coseismic, and postseismic deformation, but dominated by the coseismic part), one measurement of phase change based on two successive images con-

stitutes only one component of the three-dimensional surface displacement vector, specifically the component projected onto the spacecraft-pixel vector. In this respect, it differs from the three-dimensional vector measured by GPS.

The great advantage of SAR is that coseismic observations are acquired with virtually complete spatial coverage, rather than the sparse, generally aliased observations inherent in conventional (including GPS) geodesy. While in principle, all three components could be obtained from space, in practice, we are only likely to obtain two components from the ascending and descending passes of the satellite. Additional information, from ground observations or models, is required to determine the full three-dimensional deformation field.

The measured phase depends not only on surface changes in the period between acquisition of the two images, but also on the topography and the orientation of the vector describing the baseline between the respective antenna positions. The topographic data requirement can be met in two ways. *Massonnet et al.* [1993] used a preexisting digital elevation model (DEM) such that only two satellite passes (one before, one after) were required to measure coseismic offset. The DEM for the Mojave region is representative of digital topographic data in existence for most of the northern hemisphere (90 m by 120 m pixels, nominal vertical accuracy 30 m), but unfortunately, much of it is classified and not available for scientific research. Errors in the DEM contributed about 1 cm of noise to the coseismic offset estimate (rms vertical errors were estimated at about 24 m in the vicinity of the Landers earthquake). If high-quality DEM's are not available, the topographic data can be derived independently by the SAR, although three passes are required (the first two generate the height data, the third estimates the change). Derivation of topographic data from SAR interferometry was demonstrated by *Zebker and Goldstein* [1986]. *Zebker et al.* (submitted manuscript, 1994) describe estimation of the Landers coseismic displacement without reference to a priori elevation data with the three-pass technique.

The second requirement (antenna baseline orientation) implies accurate knowledge of the orbital parameters of the spacecraft during each image acquisition. *Massonnet et al.* [1993] tested a number of satellite passes before finding two with optimum characteristics, then adjusted the orbital parameter estimates to minimize coseismic offset far from the fault. In this case, optimum is a function of radar wavelength and the desired result (topographic height estimates versus change detection). To obtain topographic estimates from SAR interferometry, the baseline should be neither too short (otherwise sensitivity to surface change is reduced) nor too long (otherwise the geometric characteristics of the image differ by too much

and the phases of the two images cannot be compared interferometrically). For C-band (~6-cm wavelength) ERS-1 images, antenna separations of 100 to several hundred m are desirable for obtaining accurate topographic heights. For L-band (~24-cm wavelength) radar, the corresponding value is of order 1 km. On the other hand, to obtain estimates of surface change, similar imaging geometry in the before and after image is desirable, implying the shortest possible (zero length) baseline.

Measurement of Surface Displacement

Measurement of surface displacement with SAR interferometry requires that the changes not be too large (specifically that the displacement gradient across a pixel not be too large) and that the radar scattering characteristics within each pixel remain similar during the period between the images (specifically that the rms position of the surface scatterers within a pixel remain constant within a fraction, say 10%, of the radar wavelength). When the latter condition is not met, it is termed temporal decorrelation [*Zebker and Villasenor*, 1992]. This constitutes one of the major problems for the technique. Temporal decorrelation has been observed on time scales as short as a few hours (in vegetated areas experiencing windy conditions), but on the other hand the Landers results [*Massonnet et al.*, 1993] demonstrate coherence over several months (in a desert area with no storms). A more recent study indicates correlation over 14 months in this area (April 1992 to July 1993) [*Massonnet et al.*, 1994]. Qualitatively we know that desert is better than dense forest, dry conditions are better than wet, and long radar wavelength is better than short, but much work remains to be done in understanding this phenomenon.

Workshop Results and Recommendations

There was general agreement that SAR interferometry for change detection holds great promise in the fields of earthquake studies, volcano monitoring, and glacier and ice stream flow studies, while in a number of other fields such as hydrology and geomorphology, generation of an accurate, globally consistent DEM by itself would be a major advance. Each discipline came up with specific recommendations that were discussed by the entire group on the last afternoon. Five common suggestions emerged, covering both short-term goals (next one to two years, the first four items below) and longer-term goals (the fifth bulleted item below):

- Pursue research aimed at better characterizing and understanding temporal decorrelation in a variety of environments (the second flight of NASA's SIR-C instrument scheduled for late 1994 will provide valuable data for this study);
- Pursue the use of an aircraft platform for change detection, to supplement existing space-borne techniques and provide more coverage before a dedicated mission;

- Add a ground receiving station for ERS-1 data in Hawaii to enable SAR interferometric monitoring of inflation/deflation of Mauna Loa and Kilauea and deformation associated with a large potential landslide on the flank of Kilauea, and to study temporal decorrelation in a variety of environments within a single area;

- Pursue engineering studies to assess the feasibility and cost of obtaining a global topographic data set with 10-m spatial resolution;
- Pursue a dedicated space mission aimed at long-term monitoring of active earthquake zones, volcanos, and other surface change phenomena, such as glaciers and ice sheets, and for acquisition of a global DEM. To optimize the mission for interferometric change detection, it should include a longer wavelength radar, for example, L-band (24-cm wavelength), and have wide swath width (100 km or more), long duration (3 years or more), dual antennas (for same pass acquisition of high-resolution, high-accuracy topographic data), and possibly include multiple spacecraft (to enhance spatial coverage with rapid revisit times).

A twin spacecraft L-band system such as NASA's proposed Global Topography Mission can meet these requirements, but should be modified in the following ways:

- Increase mission lifetime, from 9 months to 3 years or more.
- After the initial (first 3–6 months) mapping phase for topography, modify the orbits of the spacecraft to maximize change detection capability, for example, separate the two spacecraft into different orbits.
- Increase the swath width, from presently planned 35 km to 100 km or more, at least for the second change detection phase of the mission.

Each group is preparing a written chapter that will be included in a workshop report, tentatively scheduled for distribution in August.—*T. Dixon, Rosenstiel School of Marine and Atmospheric Sciences, Division of Marine Geology and Geophysics, University of Miami, Fla.*

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